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The objective of this research project can be broadly classified as theoretical study and implementation of spread spectrum communication systems using surface acoustic wave technology. Significant progress has been made in the last 39 months towards this goal. Some of these are: 1) Measurement of the probability of error curve for a spread spectrum receiver implemented with real time SAW Fourier transformer, ii) Theoretical study of the receiver including the removal of narrowband jamming. The details of this research have been published in 14 papers and one report and presented at 11 technical conferences.

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ABSTRACT

The objective of this research project can be broadly classified as theoretical study and implementation of spread spectrum communication systems using surface acoustic wave technology. Significant progress has been made in the last 39 months towards this goal. Some of these are:

i) Measurement of the probability of error curve for a spread spectrum receiver implemented with real time SAW Fourier transformer.

ii) Theoretical study of the receiver including the removal of narrowband jamming.

The details of this research have been published in 14 papers and one report and have been presented at 11 technical conferences.

INTRODUCTION

One of the main objectives of this research project was to study and implement a spread spectrum communication system using surface acoustic wave (SAW) technology. This report will discuss what we have accomplished to date. Before getting to that, however, it is worthwhile to review the basic ideas behind our current study.

Surface acoustic wave technology is a new technology [1,2]. A SAW device is an analog device which uses Rayleigh wave propagation on $LiNbO_3$ or quartz crystals. One of its distinct advantages over alternate technologies is the high bandwidth that it can achieve. Fifty MHz bandwidth acoustic surface wave convolvers with time-bandwidth products of 1000 have been fabricated [3]. Using a tapped delay line, it is simple to implement a p-n code generator [4]. Furthermore, both ambiguity functions [5] and Fourier transforms [6] of signals can be generated using space-charge coupled acoustic surface wave devices. Some of the important building blocks required for the implementation of a spread spectrum receiver are correlators/convolvers, bandpass filters and p-n code generators. As all these devices can be advantageously fabricated using SAW technology, it is quite possible to envision most of the important components of the receiver being implemented on a single $LiNbO_3$ substrate, thereby making the unit cost of the receiver very reasonable. With the coming of age of systems such as JTIDS and SEEKTALK, the demand for such signal processing capability is continually increasing.

Classically, analog filtering techniques were performed by convolving the signal to be filtered with the impulse response of the filter. Recently, a new approach to analog filtering has been suggested, one that relies on the ability of a surface acoustic wave device to perform a real-time Fourier transformation (and/or Fourier inversion), thereby enabling one to filter in the "frequency domain" by multiplication of appropriate Fourier transforms rather than in the "time domain" by convolution. This filtering in the frequency domain allows one the flexibility of employing filters which could not be implemented in the time domain (i.e. are unrealizable). In particular, receivers using ideal bandpass filtering and ideal notch filtering have been investigated.

The Fourier transformation is accomplished in real-time by a SAW device as shown in fig. 1 in the following manner: If a signal $f(t)\, e^{j(w_o t + \Delta t^2)}$ (that is, a waveform f(t) modulating a linear FM or chirp waveform) is convolved with the signal $e^{j(w_o t - \Delta t^2)}$, the result of that convolution will be the Fourier transform [7] of f(t). Therefore, if these two waveforms are used as the two inputs to SAW convolver, the convolver output, assuming f(t) is time-limited to some value $T \leq A$, where A is the interaction time of the device (and equals the physical length of the device divided by the velocity of propagation of the SAW in the device), will be $F(\omega)$, the Fourier transform of f(t), over the range $\omega \varepsilon\ [2\Delta T, 2\Delta A]$.

Using the Fourier transformer as described above, the general form of the receiver is shown in Fig. 2. It consists of a Fourier transformer, a multiplier, an inverse Fourier transformer, and a matched filter. In essence, the filtering by the transfer function $H(\omega)$ is performed by multiplication followed by inverse transformation rather than by convolution. This multiplication, while ostensibly being performed in the "frequency domain", is of course accomplished by the SAW device in real-time.

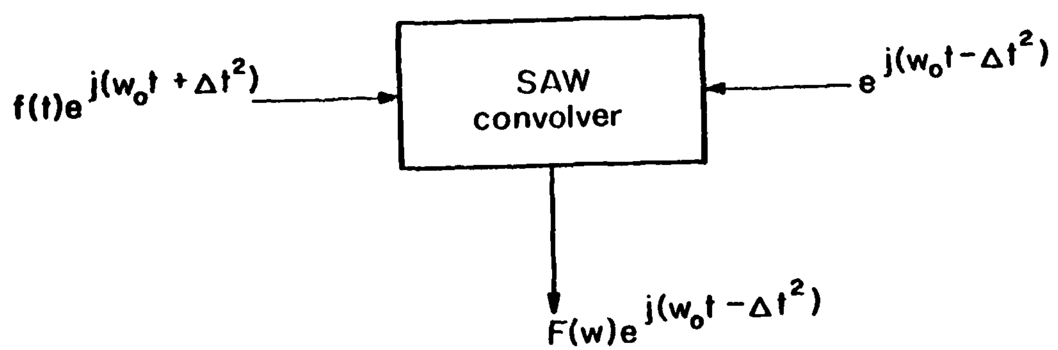

Fig. 1 Schematic of real time Fourier Transformer implemented with SAW Devices

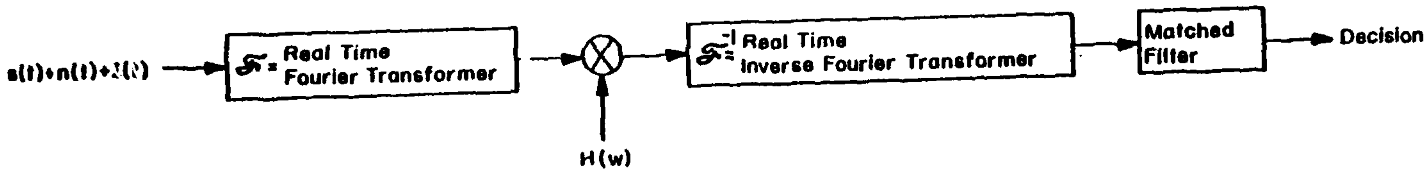

Fig. 2 SAW Implemented Receiver

SUMMARY OF TASKS COMPLETED

Significant progress has been made in the last 39 months towards the theoretical study and implementation of a spread spectrum communication system using surface acoustic wave technology. The results obtained from these studies have been well documented as indicated in the accompanying list of papers (published and to be published), report, and list of presentations at national and international meetings (Appendix). Although a detailed look at the progress we have made to date can be obtained from the above-mentioned papers, a concise summary of significant results is included in this section.

The original proposal dealt only with a very specific system, namely one where the interference was a Gaussian random process with a slowly varying covariance function. The block diagram of the original system is shown in Figure 3. However, it became clear almost immediately after we started work on the grant that the general system configuration we were proposing was applicable to a more general class of interferers. In particular, it was clear that using the same block diagram but replacing the prewhitening filter with a notch filter resulted in a system ideally suited for the removal of a narrowband interferer such as a tone jammer. Hence the work we have accomplished to date includes part of what was originally proposed plus part of some obvious extensions of that original proposal.

The theory for the nonadaptive systems has been completed for the narrowband jammer and is close to completion for the wideband, stationary, colored, Gaussian jammer. When the tone jammer used in the narrowband case is allowed to vary (i.e. change its frequency), one can use an adaptive receiver consisting of a notch filter with a variable position for the

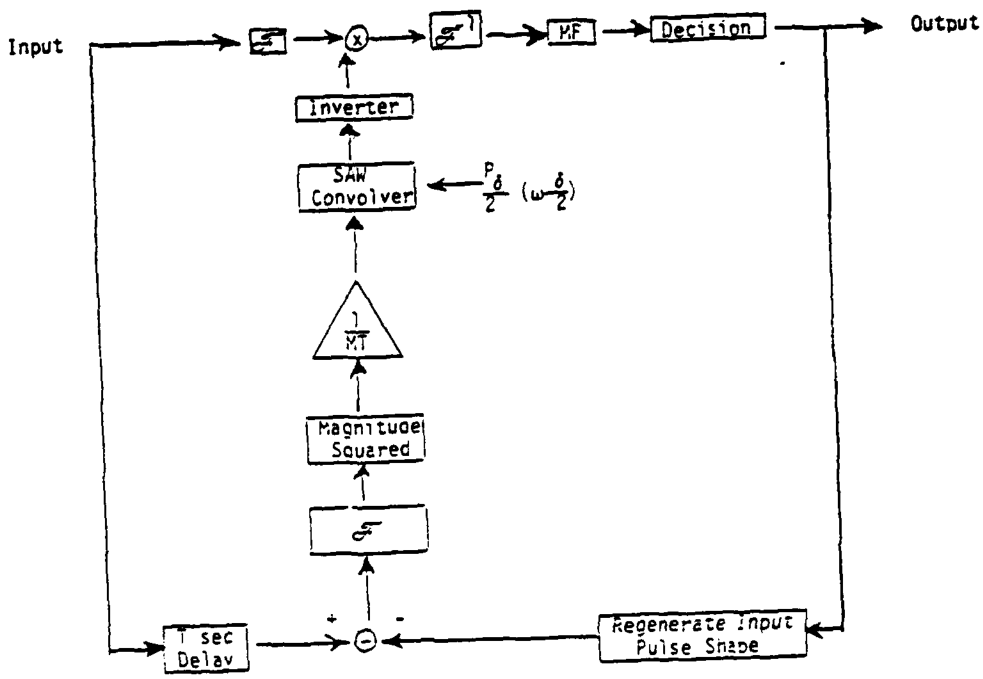

Figure 3. Adaptive Receiver

center of the notch. A system of this type has been experimentally demonstrated and is discussed in paper No. 11 (See Appendix). Most of the theory for both the variable tone jammer and the stationary Gaussian jammer has been completed, as well as all the experimental work for the tone jammer. The ability of the transform domain processing system to remove narrowband jamming has been demonstrated both analytically and experimentally. Figures 4 and 5, taken from [8] and [9] respectively, show the improvement in probability of error over a matched filter receiver when a tone jammer is present. One of the most interesting side results has been the realization of the ease with which it is possible to implement idealized filters such as perfect rectangular filters which of course are physically unrealizable using the classical approach to filtering, since they are not causal. As discussed fully in [8], using transform domain filtering, they are not only realizable, but are completely trivial to implement. Another key result described in [8] and [9] is a technique to eliminate intersymbol interference between adjacent data symbols. From a strictly experimental point of view, the implementation of the test setup itself demonstrated the ability to successfully employ SAW devices in a complete communication system, and resulted in specific techniques which will make future system measurements much more straightforward.

The final area of study of our research is quite distinct from the general flavor of the rest of the work. It arose initially as just a side issue and is concerned with the ability of SAW devices to perform real time Hilbert Transform (See papers 12 and 13 in the Appendix). The important points of this part of the research are as follows:

1) A wideband implementation of Single Side Band (SSB) generation.

2) The use of the Hilbert Transform to double the information rate of a spread spectrum communication system.

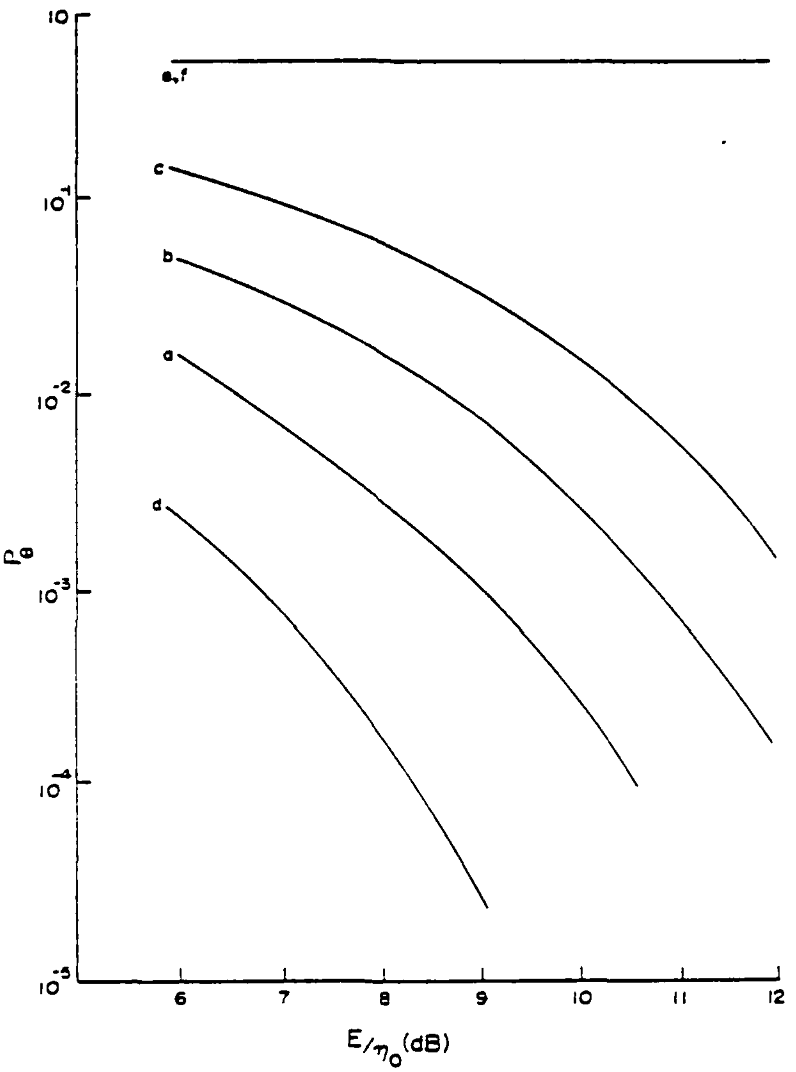

Fig. 4 Theoretical probability of error curves for the SAW-implemented receiver. $2B\ T_c = 2$, $2B$ = R.F. Bandwidth and T_c = chip duration

	Curve	Jammer/signal in db at E/η_o = 6 db
notch present	a	$-\infty$
	b	12
	c	18
notch absent	d	$-\infty$
	e	12
	f	18

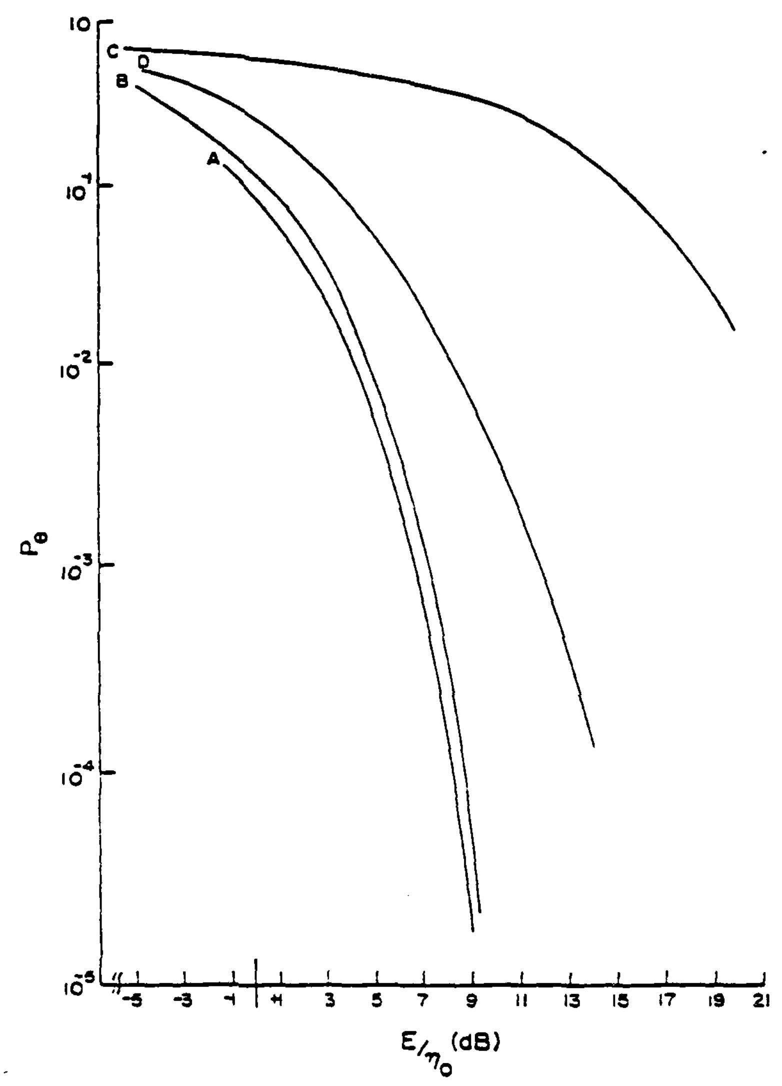

Fig. 5 Probability of error curves for the noncontiguous correlating receiver. 2B Tc = 10, 2B = R.F. Bandwidth, Tc - chip duration

a) Theoretical Curve
b) Measured performance with no jammer
c) Measured performance of system without notch when 18 db jammer present (at E/η_0 = 13 db)
d) Measured performance of system with notch when 18 db jammer present.

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APPENDIX

List of papers published and to be published under the auspices of this grant

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14. D. Shklarsky, P. Das and L. B. Milstein, "Doppler Insensitive Time Integrating Correlator Using SAW Convolver and CCD", 1980 Ultrasonics Symposium Proceedings, to be published.

15. D. Shklarsky, P. Das and L. B. Milstein, "A SAW filter for SSB Waveform Generation", IEEE Trans. Circuits and Systems, Vol. CAS-27, pp. 464-468, 1980.

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1. D. R. Arsenault, L. B. Milstein and P. Das, "Signal Processing Using Surface Acoustic Wave Devices and its Application to Spread Spectrum Communication Systems", Technical Report MA-ARO-10, Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, 317 pages, Dec. 13, 1979.

APPENDIX (cont'd)

List of papers presented in national and international meetings

1. D. R. Arsenault and P. Das, "SAW Fresnel Transform Devices and Their Applications", presented at the 1977 IEEE Ultrasonics Symposium, Phoenix, Arizona, October 1977.

2. P. Das, L. B. Milstein and D. R. Arsenault, "Adaptive Spread Spectrum Receiver using SAW Technology", presented at the National Telecommunication Conference, December 5-8, 1977, Los Angeles, Cálifornia.

3. L. B. Milstein, D. R. Arsenault and P. Das, "Transform Domain Processing for Digital Communications Systems using Surface Acoustic Wave Devices", presented at the AGARD-NATO conference on Digital Communications, Munich, Germany, June 5-9, 1978.

4. D. R. Arsenault, P. Das and L. B. Milstein, "Matched Filtering of Continuous Signals by the Product of Transforms Technique using SAW Chirp Filters", presented at the 1978 Ultrasonics Symposium held at Cherry Hill, NJ, September 25-27, 1978.

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6. L. B. Milstein, D. R. Arsenault and P. Das, "Signal Processing with SAW Devices", presented at the International Telemetering Conference, Los Angeles, Nov. 14-16, 1978.

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